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Experimental–Numerical Characterization of the Fracture Behaviour of P264GH Steel Notched Pipes Subject to Internal Pressure

Hassane Moustabchir¹  · Azari Zitouni² · Said Hariri³ · J. Gilgert² · C. I. Pruncu⁴

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Abstract The rupture phenomenon of a mechanical structure requires critical consideration, because of its safety constructions. A detailed experiment of material features as well as the Young's modulus, yield strength, material toughness or fracture resistance provides useful information to predict the life integrity of a pipe structure. This paper presents the most accurate experimental techniques for characterization of a pipe-like structure to assess its reliability. Standard traction tests, dynamic Charpy tests and pressure tests were performed to envisage the crack propagation progress. Detailed information on fracture process was obtained by a robust numerical approach using the finite element method.

Keywords Fracture toughness · Stress intensity factor · Volumetric method · Notched pipe

1 Introduction

Gas production sites are often very far from consumption centres. To increase the profitability of a pipeline, the use of large tubular structures is appropriate under high pressure. From 1910 to 2000, the diameter of the largest “transport” pipelines was multiplied by 4 and the transport pressure by a value of 60. These increases were possible thanks to great improvements of mechanical properties of the steels used as design tools.

The structural integrity of the pipeline must be guaranteed to avoid any fracture damage. History emphasizes the probability of rupture is never zero. Statistical investigation, established by the European Gas Pipeline Incident Group (Association française pour les règles de conception et de construction des matériels des chaudières électro-nucléaires 1993), identifies 1060 cases of fracture in service between 1970 and 2001. Fifty percentage of these fractures are caused by “external aggression”, and other causes of significant incidents are due to the presence of defects in the material (17%), corrosion (15%) or soil movements (7%).

A simple and very economical tool to predict the pipeline integrity is the volumetric method designed on the notch stress intensity factor concept. The volumetric approach is a semi-local method evaluating the elastoplastic fracture regime based on the numerical configuration of the so-called finite element method (Elminor 2003; Adib and Pluvinaud 2003). This method was firstly applied at the Mechanical Reliability Laboratory of University of Metz. It assumes that the damage processes happening on material to fracture requires a physical volume characterized by an effective distance x_{eff} . In that volume, an effective stress is released, acting as an average weight stress surrounded by the stress distribution of the fracture process zone.

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Originally, Kuguel (1961) suggested taking into account not only the maximum surface stress (hot spot), but also the volume of the core metal stressed at least equal to 95% of the stress surface. An extension of this approach is to apply depth stress characteristic (Neuber 1968), stress at the typical depth (Buch 1974) and the stress gradient (Brand and Sutterlin 1980). Fracture progress follows a cylindrical shape, and its diameter “characteristic distance” is of the order of the grain size for the case of a crack (Ritchie et al. 1973). A critical load, load proportional to the change in the volume, may induce the fracture process (Bermin 1983), while this volume represents the plastic zone. Later on, Barson et al. (1974) and Clark (1974) described the typical distance to be the order of magnitude equal to the radius of notch.

Subsequent studies (Pluvinae et al. 1999; Pluvinae 1998; Boukharouba and Pluvinae 1999) demonstrated that this distance is not linked to the geometry of the notch, but rather to the stress distribution. This distance may relay to a pseudo-stress singularity zone appearing at the x_{eff} distance from the bottom of the notch. Moreover, this effective distance is the distance from the crack progress to the fracture process zone. Pluvinae (1997) confirmed that the magnitude of the effective stress is less than the magnitude of the maximum stress. The calculation of the stress amplitude must enclose the effects of plastic relaxation.

In order to describe the loading condition or the scale effect (Qylafku 2000), the needs of calculating the stress amplitude from a volume called “volume of fracture process” may be compulsory. The amplitude of the effective stress should consider the state of stress gradient in the volume of fracture process. The importance of this gradient and its role in the rupture initiation point has been reported by various authors (Peterson 1959).

This survey aims to provide a better understanding of how to evaluate the pipeline integrity using the volumetric method designed on the notch stress intensity factor concept. In order to prove the robustness of the present approach, the elastoplastic zone was considered. The results were then validated by detecting the material fracture toughness with a classical dynamic Charpy's test.

2 Computing the Notch Stress Intensity Factor in Mode I

The notch stress intensity factor (NSIF) was accurately determined by Qylafku et al. (1999) considering the volumetric approach, based on the effective stress σ_{eff} and the effective distance x_{eff} . Boukharouba et al. (1995) and Pluvinae (1997) achieved good results in elastic domain and then extended the analysis to elastic–plastic material behaviour. Qilafku (2001) reveal good progress in determining the NSIF in the “elastoplastic” mode I.

Figure 1 presents the stress distribution computed via FEM analysis following the volumetric approach (VA) tool. There, the elastoplastic stress (opening stress at fracture) and the stress gradient are depicted. This diagram includes four specific areas:

Zone I Region close to the initiation point where the elastic–plastic stress, at the crack tip, increases up to the maximum stress. Note that the stress is not maximum at the notch root, but is offset by a certain distance.

Zone II The elastic–plastic stress decreases up to the effective distance x_{eff} .

Zone III The evolution of elastoplastic stress has a linear behaviour in the logarithmic chart. This behaviour is expressed by a power law:

$$\sigma_{ij}(\theta) = \frac{K_p}{(2\pi r)^\alpha} f(\theta) \quad (1)$$

where K_p is the notch stress intensity factor, r distance from the initiation point, $\alpha = 1/2$ (case of a sharp crack), ϕ polar angle.

Zone IV This area is far from bottom of the notch and plays no role in the rupture process.

The stress gradient along the x -distance, expressing the influence of stress points on the fracture initiation, is determined:

$$\text{grad}\sigma = \frac{d\sigma}{dx} \quad (2)$$

The effective distance corresponds to a diameter of a cylindrical profile considered as the volume of fracture processes. To determine this effective distance, (Qilafku et al. 2001) used the relative stress gradient, defined as the ratio of the stress gradient and the stress $\sigma(x)$:

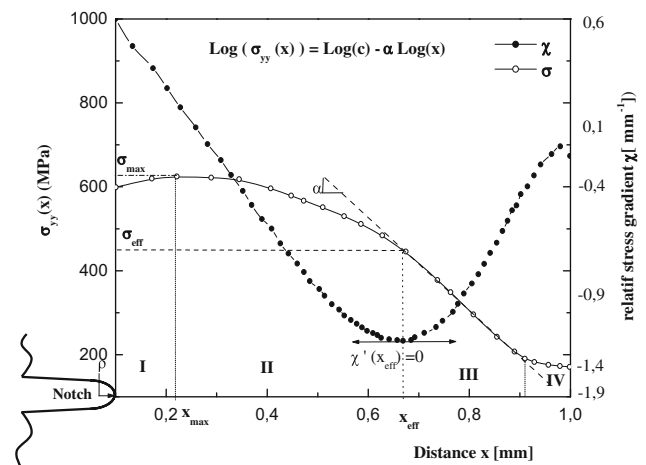


Fig. 1 Bilogarithmic diagram of the stress distribution σ_{yy} and the gradient elastoplastic stresses obtained by finite element (Qilafku et al. 2001)

$$\chi = \frac{1}{\sigma(x)} \frac{d\sigma(x)}{dx} \quad (3)$$

where χ is the gradient relative of stress (mm^{-1}) and x distance (mm).

The effective stress (σ_{eff}) is the weighted average of the stresses enclosed into the volume of the fracture process zone, determined as:

$$\sigma_{\text{eff}} = \frac{1}{x_{\text{eff}}} \int_0^{x_{\text{eff}}} \sigma_{ij}(1 - x\chi) dx \quad (4)$$

The maximum stress intensity factor is determined by:

$$K = \sigma_{\text{eff}} \sqrt{2\pi x_{\text{eff}}} \quad (5)$$

3 Experimental Procedure

3.1 Material and Specimens

The material characterization was performed on the P264GH steel specimens. The samples were collected from a pipe having the external diameter of 610 mm and a thickness of 11 mm. That pipeline was used in the 50 s and then removed at the beginning of the twenty-first century. The extracted samples conform to the longitudinal direction (L) as depicted in Fig. 2. Their chemical characteristics may differ very little from the standard and are summarized in Table 1.

The microstructure of P264GH steel samples was analysed by optical microscopy after mechanical polishing and chemical treatment with 2% natal. The metallographic analysis confirms that the sheet used in the manufacture of this pipe is rolled in both directions (L and T). We have observed bands of perlite (coloured in black) alternating with bands of ferrite (coloured in white) which is a sign of rolling machining. Figure 3 shows that ferrite is the main component of this microstructure (Fig 4).

The tensile tests were performed at room temperature. For that purpose, six cylindrical specimens of diameter

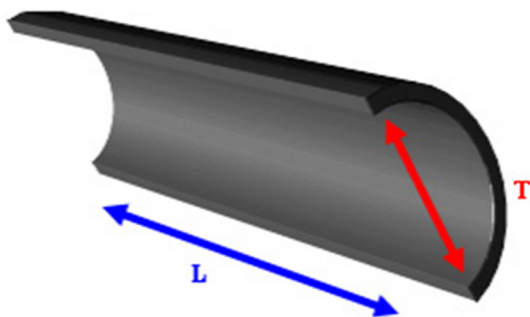


Fig. 2 Longitudinal and transversal directions of a pipeline

7 mm and cross circular section S_0 were machined. These specimens have a total length (L_t), an initial length (L_0) and a gauge length (L_c), as shown in Fig. 3.

With: $L_0 = k\sqrt{s_0}$; $k = 5, 65$; $L_0 + \frac{d}{2} < L_c < L_0 + 2d$ and $L_t \geq L_c + 2d$

Figure 5 shows the experimentally determined stress-strain curve. The tested material follows a ductile behaviour.

The main mechanical characteristics obtained are listed in Table 2:

3.2 Dynamical Characterization: Charpy Test

The critical notch stress intensity factor was determined by the Charpy test. The tests were used to characterize the fragility of the material. The main parameter measured was the material resilience which corresponds to the value of energy absorbed per unit of area.

The resilience KCV is defined as the work of fracture per unit of area of the ligament without notch. It is expressed by the critical value of the fracture toughness J_{Ic} of the energy parameter J .

Material toughness is proportional to the work of fracture surface. The work of the fracture surface is defined as the work of fracture U_c per unit of area with the ligament length of $w.b$. (w is the width of the specimen; b is the ligament) as plotted in Fig. 6. This work of the fracture surface is exactly the resilience rate.

$$\text{KCV} = U_c / wb \quad (6)$$

The fracture toughness at the initiation stage may be defined:

$$J_{Ic} = \eta U_c / wb = \eta \text{KCV} \quad (7)$$

The proportionality factor η can be determined by two methods:

- Formulae ASTM 813.81 (American standard):

$$\eta = 2 + (0.522b/w) \quad (8)$$

- Formulae BS (British standard):

$$\eta = 1.97 + (0.518b/w) \quad (9)$$

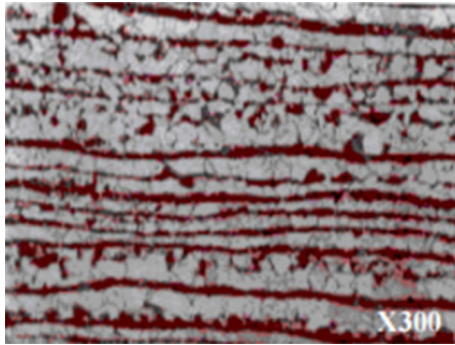
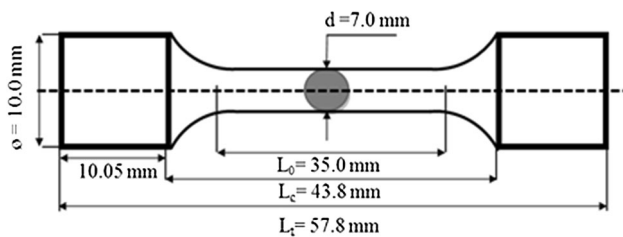
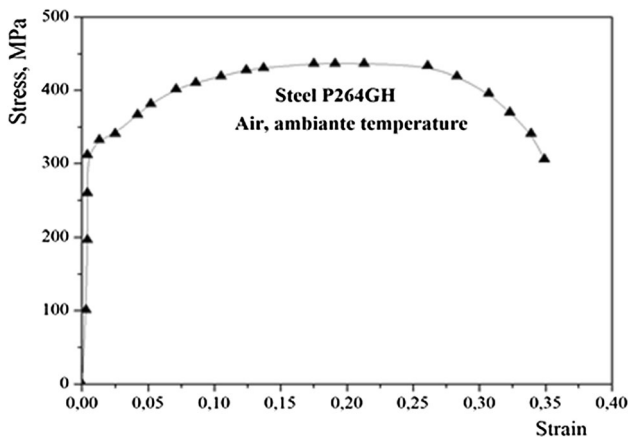
where b is the size of ligament sample and w sample width.

The toughness K_{Ic} varies depending on the energy absorbed by the standard Charpy V-notch. The fracture toughness K_{Ic} increases linearly with the energy absorbed by the test Charpy V. A picture with the sample profiles used in these tests is depicted in Fig. 7.

Charpy tests were performed in two different directions as shown in Fig. 7

Table 1 Chemical composition of P264GH steel sample (wt%)

Material	C	Mn	Si	S	P	Al	Fe
Steel sample tested	0.123	0.665	0.195	0.002	0.013	0.027	Bal.
Steel P264GH according to standard EN 10028.2-92	0.18	1	0.4	0.015	0.025	0.02	Bal.

**Fig. 3** A replica of P264GH steel sample microstructure**Fig. 4** Geometry and dimensions of the tensile test specimens**Fig. 5** Static stress–strain curve of P264GH steel obtained from 1D tensile test

- L samples (refers to the longitudinal direction of rolling)
- T samples (designates the transverse direction).

The values of the fracture energy for each sample during testing routine are listed in Table 3. The values of the

Table 2 Mechanical characteristics, at room temperature, of P264GH steel samples

Young's modulus	$E = 207,000 \text{ MPa}$
Poisson's ratio	$\nu = 0.3$
Yield stress	$R_e = 340 \text{ MPa}$
Ultimate tensile strength	$R_m = 440 \text{ MPa}$
Elongation to fracture	$A = 35\%$

resilience KCV are determined from Eq. (6), and the fracture toughness J_{Ic} was obtained from Eq. (7), while the values of the critical notch stresses intensity factor K_{Ic} were determined as a function of KCV from the curve plotted in Fig. 8.

$$J_{Ic} = \eta KCV \quad (10)$$

The value of η was determined by Formula 813.81 ASTM (American Standard):

$$\eta = 2 + (0.522b/w) \quad (11)$$

that gives:

$$\eta_{\text{moy}} = 2, 3.$$

$$K_{Ic} \left[\text{MPa} \times m^{1/2} \right]$$

The error of the notch stress intensity factor between samples in the transverse direction and in the longitudinal direction, respectively, is only 4%. This indicates that the material is relatively isotropic.

The behaviour of the P264GH steel, subjected to dynamic experiment “Charpy V” test, was analysed, and the potential of material's ability to absorb the energy until final fracture was assessed from Charpy tests. Experimental results show that the fracture toughness of the samples, in the transverse direction, is closer to the fracture toughness of a standard sample. Material isotropy is more evident in the longitudinal direction.

3.3 Study of Defect Harmfulness in the Pressurized Pipe

We performed a rupture test on the structure made of steel “P264GH”. The test used is a “pressurized chamber” with axial default.

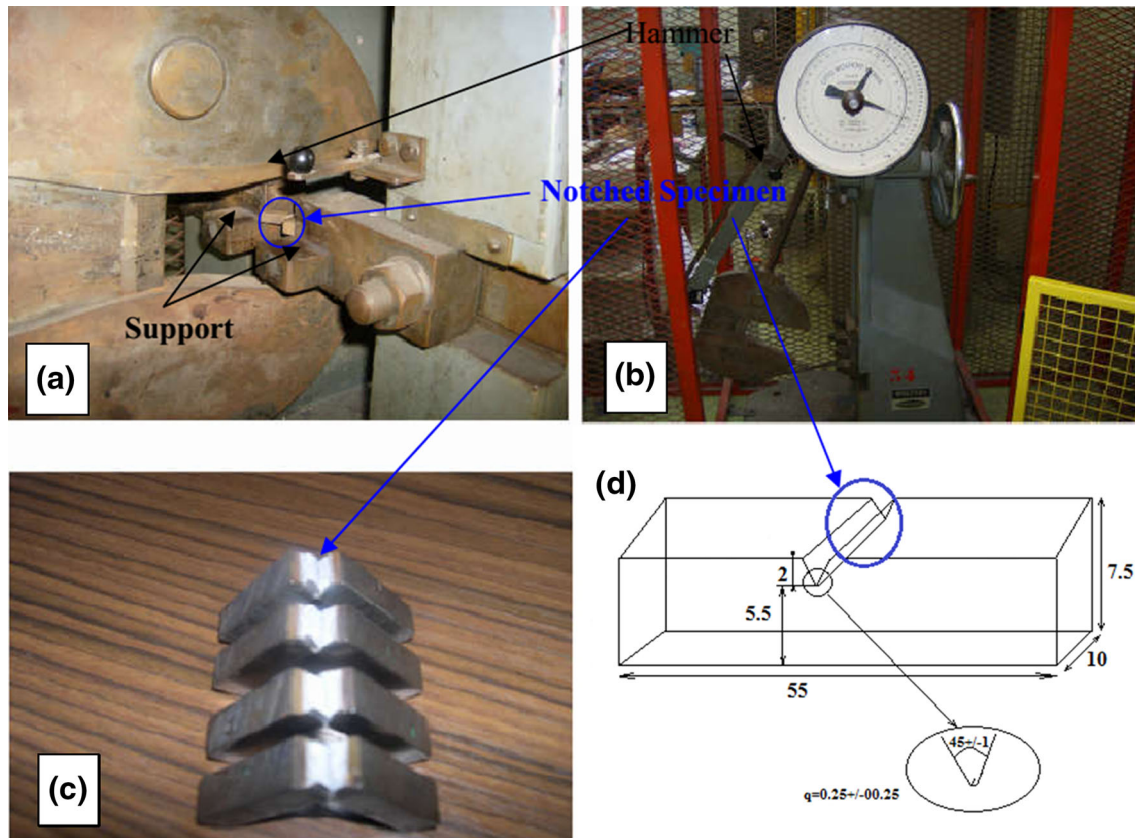


Fig. 6 Details of entire experiment. **a** Cylindrical shell, **b** Charpy machine used in this study, **c** notched samples after test and **d** details of the geometrical dimensional size of the tested samples with V-notch

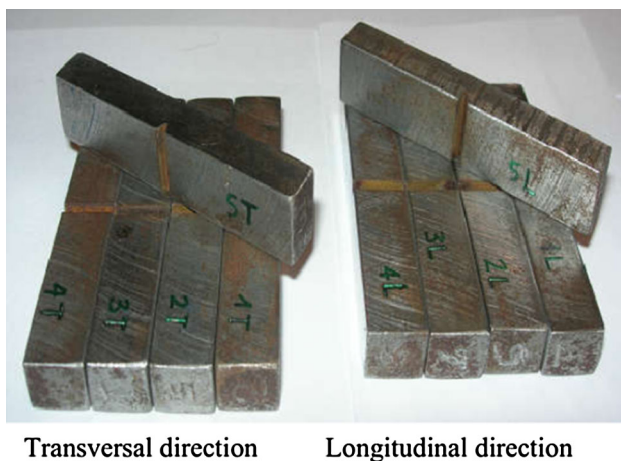


Fig. 7 Specimens utilized in Charpy impact tests

3.3.1 Structural Characterization

The mechanical characterization was performed on a model consisting of a cylindrical shell closed by two types of torispherical head with large radius. The geometry of the

analysed component, selected according to CODAP standard, is shown in detail in Fig. 9. In that study, a longitudinal surface crack that represents a very high risk of pipe fracture during pressurizing (Moustabchir et al. 2016) was considered. Table 4 summarizes the dimensions and orientations of the defect.

The model equipped with the strain gauges was pressurized. The maximum deformation is sensed by the closest strain gauge to the defect.

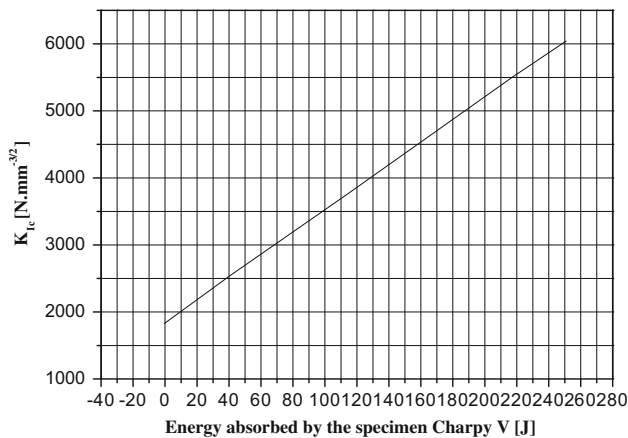
Figure 10 shows the pressure (in bar) as a function of circumferential deformation $\epsilon_{\theta\theta}$ recorded by the gauge J_1 , J_2 situated on the longitudinal chain of the defect C1.

From the curve, relative to the nearest strain gauge to the defect D , it is possible to see that the deformation zone passes into the plastic range around 40 bar. The data relative to second gauge (located at 4 mm from the defect) indicate that the material enters in the plastic regime at about 43 bar pressure.

In summary, the material becomes more stressed in the vicinity of the defect D , while the plastic range is obtained for a pressure above 40 bar.

Table 3 Results of Charpy tests

Number of samples	Energy absorbed at fracture KV (Joules) (Charpy tests)	Energy average KV	Resilience KCV (MJ/m ²)	Average resilience KCV (MJ/m ²)	Factor η	Average factor η	J_{Ic} (MJ/m ²)	J_{Ic} average (MJ/m ²)	NSIF K_{Ic} (MPa m ^{1/2})	NSIF average K_{Ic} (MPa m ^{1/2})
<i>Transverse direction</i>										
1	86.3	80.54	1.57	1.48	2.29	2.29M	3.59	3.37	102.77	99.13
2	80.2		1.49		2.28		3.39		99.06	
3	74.2		1.4		2.28		3.19		94.87	
4	80		1.48		2.28		3.37		98.82	
5	82		1.44		2.3		3.31		100.14	
<i>Longitudinal direction</i>										
6	64	72.58	1.10	1.27	2.3	2.3	2.53	2.91	90.91	94.99
7	84.1		1.45		2.3		3.33		101.45	
8	76		1.31		2.3		3.01		97.50	
9	67.8		1.23		2.29		2.82		92.23	
10	71		1.24		2.3		2.85		92.89	

**Fig. 8** The notch stress intensity factor K_{Ic} , as a function of the energy absorbed by the Charpy V piece (British Standards Institution PD 6493 1991)

4 Numerical Analysis of Defect Harmfulness in the Pressurized Pipe

In order to consider the elastoplastic regime, cylindrical shells with outer axisymmetric notch were subjected to an internal pressure of 60 bar (value is consistent with the plastic field, Fig. 10). The model considered was axisymmetric. The notch stress intensity factor was computed at the bottom of defect and then analysed. Its distribution allows detection if the pressure of 60 bar in the elastoplastic domain exceeds the critical stress intensity factor which has been obtained from Charpy's test. Geometric parameters were set as follows: $alt = 0.2$; $t/R = 0.052$; $c/a = 4$ and $\rho = 0.25$ mm.

The structures were modelled by CASTEM 2000, in agreement with (Moustabchir et al. 2010, 2012) under

plane strain conditions using free-meshed iso-parametric quadrilateral elements, i th quarter-point singularity elements at the crack tip. It was enough to model half of the structure because of symmetry in the geometry and loading conditions. The mesh generated from the elastoplastic analyses comprises 31,485 elements and 63,526 nodes. The mesh convergence was achieved for the element size of 2 mm. The FE model utilized in the numerical simulations is illustrated in Fig. 11.

The stress distribution calculated in the elastoplastic region is characterized by a stress relaxation at a distance greater than 0.1 mm from the notch.

Figure 12 shows the distributions of elastoplastic stress, for the 60 bar pressure and for a radius at the bottom of notch $\rho = 0.25$ mm. The choice of this pressure prevents the elastic case, while we detected that the plastic limit started at 42 bar during the experimental tests.

5 Computing the Notch Stress Intensity Factor by Volumetric Approach

The volumetric approach allows finding the effective distance and effective stress from the diagram of the stress distribution.

In zone II (set as $r \geq r_{ref}$), the stress can be represented by a relation of the type:

$$\sigma_{yy} = \frac{K_{\rho}}{\sqrt{2\pi r}} \quad (12)$$

where K_{ρ} is the notch stress intensity factor, expressed in MPa (m)^{1/2}.

Fig. 9 **a** Schematic of the pressurized pipe model and 3D view of the instrumented specimen, **b** position of the defect, **c** position of gauge chains near a fault D

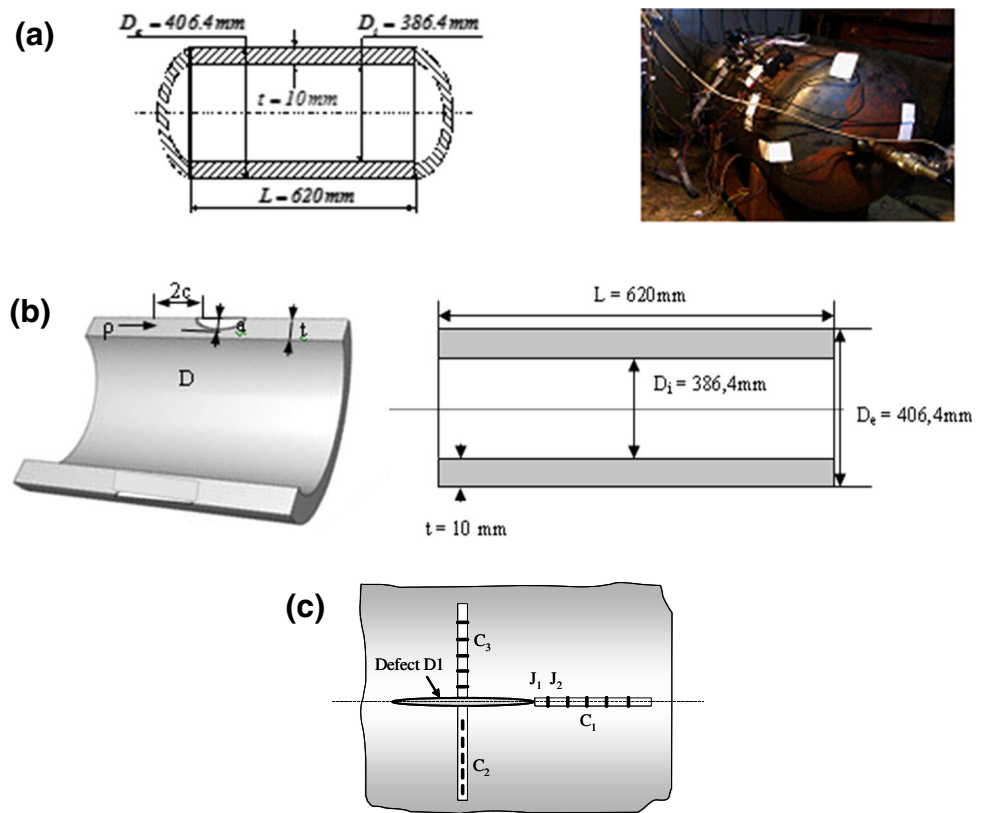


Table 4 Dimensions of defect studied

Defects	Orientations	Dimensions (mm)
Semi-elliptical (D)	Axial	$a = 2, t = 10$ $c = 8$ $\rho = 0,25$

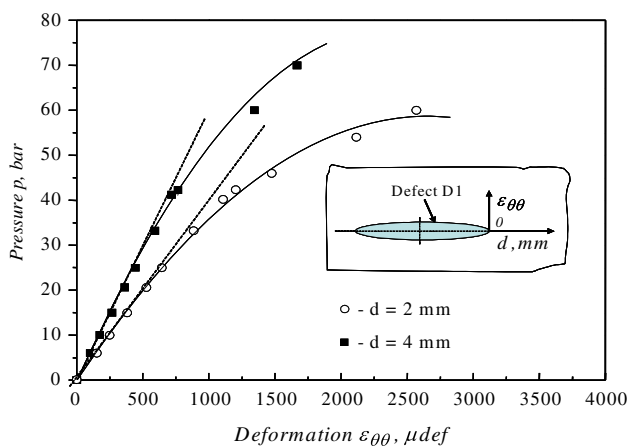


Fig. 10 Deformation of the gauge (J_1, J_2) as a function of the pressure in the case of longitudinal default

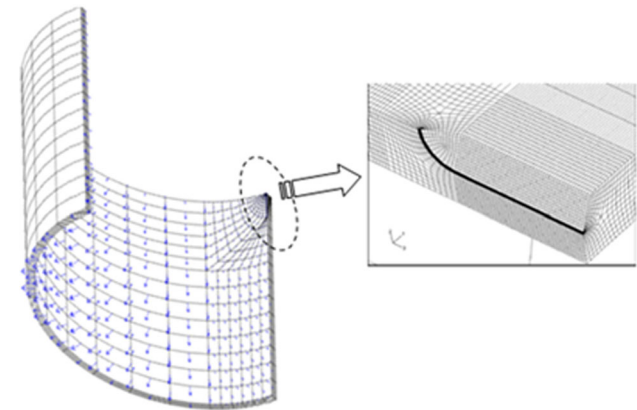


Fig. 11 A typical mesh adopted in the simulation routine

The equation describing the NSIF in mode I is:

$$\sigma_{yy} = \frac{K_{I\rho}}{\sqrt{2\pi X}} \quad (13)$$

where X is the distance along the axis of abscissa (x -axis), σ_{yy} stress in MPa and $K_{I\rho}$ the notch stress intensity factor in mode I, expressed in $\text{MPa (m)}^{1/2}$. At the boundary of zone II and for $r = X_{\text{eff}}$, the NSIF, expressed in terms of r_{eff} and σ_{eff} , becomes:

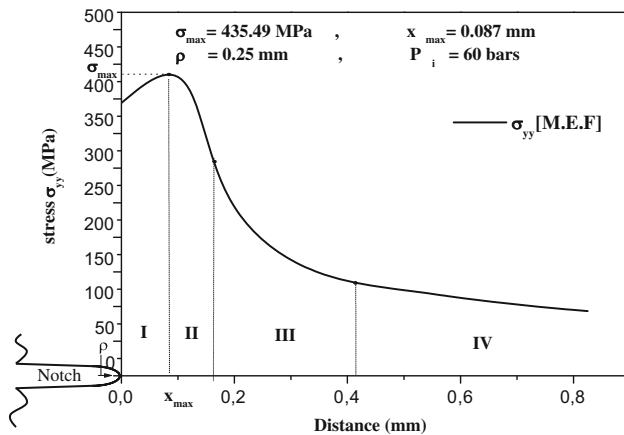


Fig. 12 Variation of circumferential stress with the distance from the defect computed by elastoplastic FE analysis

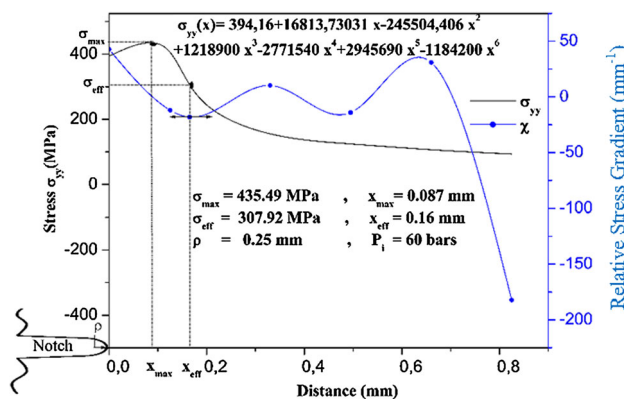


Fig. 13 Determination of notch stress intensity factor from the volumetric method

$$K_p = \sigma_{\text{eff}} \sqrt{2\pi X_{\text{eff}}} \quad (14)$$

Where X_{eff} is the effective distance, σ_{eff} effective stress and K_p the notch stress intensity factor in mode I.

The above equation connected to the stress distribution curve permits determining the relative gradient (see Fig. 13). At the inflection point of this curve, we get the actual distance and the effective stress.

Accurate fitting leads to determine an effective distance of $X_{\text{eff}} = 0.16$ mm corresponding to an effective stress of 307.92 MPa.

The volumetric method allows the K_{Ip} to be calculated as follows:

$$K_p = 307.92 \sqrt{2\pi \cdot 0.16 \times 0.001}$$

That gives:

$$K_p = 9.76 \text{ MPa } (m^{1/2})$$

6 Conclusion

Charpy's test is a very robust methodology for accurately detecting the material behaviour even in the presence of small modifications. When linear fracture mechanics was developed, a radical revision was introduced. In 1970, the impact testing procedure was improved using the fracture toughness parameter under the impact test in terms of critical stress intensity factor/critical strain energy release rate. However, regardless of all these variants, Charpy's test remains one of the best experimental solutions to verify the consistency of the materials for structural applications.

This study investigated the mechanical behaviour of notched steel pipes subject to internal pressure. The characterization in terms of fracture toughness was performed in both directions (i.e. longitudinal/transversal), demonstrating the isotropy of P264GH steel.

Numerical simulations were specifically developed for the elastoplastic regime where the evolution of the stress distribution is a nonlinear function. Despite an applied pressure of 60 bar, the notch stress intensity factor calculated for the case of a longitudinal crack remains low. Computed values of NSIF are very conservative. This indicates that the 60 bar pressure considered in the simulations does not exceed the critical stress intensity factor determined by Charpy tests.

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